Aerospace applications of laser additive manufacturing

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13.1 Introduction

Additive manufacturing (AM) has been used in aerospace applications from the beginning. In the late 1980s the first commercial rapid prototyping machine was developed at 3D Systems. The American aerospace manufacturer Pratt & Whitney was one of the first five customers [1]. Boeing, for example, has approximately 300 different part numbers on 10 different aircraft production programs, which amounts to more than 20,000 nonmetallic additive manufactured parts that are on vehicles delivered to their customers. Approximately 150 parts in the forward fuselage area of the F/A-18 Super Hornet are produced through selective laser sintering [2]. AM, which is a completely new manufacturing process compared with the conventional subtractive manufacturing process, has profoundly influenced product design, manufacturing, and assembly in the aerospace industry. It not only plays a role as a rapid prototyping technology for saving capital and time during the product development period, it can also be adopted for rapid tooling, direct part manufacturing, and repair in the aerospace industry. Because of recent developments, AM has rapidly become a strategic technology that will generate revenue throughout the aerospace supply chain [3]. This chapter discusses new opportunities and benefits brought by AM technologies for aerospace applications.

This chapter is organized with the following structure. Section 13.1 gives a brief introduction of aerospace applications of AM and discusses the characteristics of aerospace components favoring AM. Section 13.2 describes metallic and nonmetallic aerospace components fabricated by different AM processes. Section 13.3 discusses repair applications for aerospace components, illustrating the advantages, general processes using AM for repair. Application examples both from commercial and academia areas are analyzed in Section 13.1 and 13.2. Finally, this chapter discusses the challenges of applying AM to the aerospace industry and potential future aerospace applications.

13.1.1 Characteristics of aerospace components favoring additive manufacturing

Aerospace components usually have the following characteristics, which make them highly suitable for fabrication by AM:

- *Components have a complex geometry or a large volume envelope—to—volume ratio*: Aerospace components often have complex geometries because aerospace applications

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usually require components with integrated functions. For instance, structural components may also act as conduits, such as an airfoil with an embedded cooling channel or an engine turbine blade that may also have an internal structure for coolant. Furthermore, geometric specifications of parts may be defined by complex mathematical formulae based on, for example, fluid flow. On the other hand, many aerospace components have a large volume envelope—to—volume ratio, as in thin-walled structures for example, combustion chambers or a turbine blade. Those features make the tool path planning algorithm very complicated, time-consuming, and material-consuming by conventional computer numerical control (CNC) machining. The capability for freeform fabrication makes AM very suitable for these kinds of aerospace components.

- *Difficult-to-machine parts and high buy-to-fly ratio*: Aerospace components are usually made from advanced materials, such as titanium alloys, nickel-based superalloys, special steels, or ultrahigh-temperature ceramics, which are difficult, costly, and time-consuming to manufacture. In addition, current buy-to-fly ratios result in a massive waste of materials.
- *Small production runs*: AM processes tend to be more expensive for large production runs than conventional machining processes. Compared with the conventional machining processes, however, AM does not need design and fabricate fixtures, molds, or dies. Therefore AM is most competitive for customized parts and applications with small production runs, which are common in the aerospace industry.
- *Parts that need quick turnaround time*: Many aircraft have a long working life; some airplanes have an average service life of more than 30 years. Maintaining and replacing old tooling is a notable inventory cost for manufacturers. AM enables these parts to be quickly shipped and installed in a broken plane to help get it back in the air and making money for the airline [3]. According to Airbus, the turnaround for test or replacement parts can now be as short as 2 weeks.
- *High-performance parts*: Aerospace components require that materials be lightweight with a high strength-to-weight ratio to improve fuel efficiency and reduce emissions. Furthermore, some aerospace components work in extreme conditions, such as ultrahigh or low temperatures or extreme chemical environments. Engine components are subject to very high temperatures in which innovative cooling solutions are used and internal components are required to be made from flame-retardant materials. AM brings new opportunities to fabricate tailored parts in aerospace applications [1].

13.2 Aerospace component fabrication with additive manufacturing

13.2.1 Overview of additive manufacturing methods for aerospace applications

In the manufacturing industry, the main applications of additive manufacturing include rapid prototyping, rapid tooling, direct part production, and part repair of metal, plastic, ceramic, and composite materials [4]. Both metallic and nonmetallic parts fabricated by AM technology have potential applications in the aerospace industry. A number of different technologies developed for metal AM processes can be classified by the energy source (laser beam, electron beam, and arc), feedstock state (metal powder, wire, and sheet), or the method of feed material (blown powder and powder

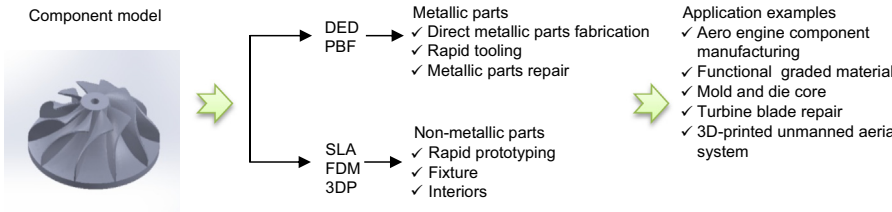

Figure 13.1 Overview of additive manufacturing methods for aerospace applications. *3D*, three-dimensional; *3DP*, three-dimensional printing; *DED*, directed energy deposition; *FDM*, fused deposition modeling; *PBF*, powder bed fusion; *SLA*, stereolithography.

bed). The two primary metal AM categories are (1) directed energy deposition (DED) [5–7], which covers laser metal deposition (LMD)—also known as laser engineering net-shape (LENS) or direct metal deposition—and electron beam free-form fabrication [8]; and (2) powder bed fusion (PBF), which includes selective laser sintering [9], selective laser melting (SLM) [10], and electron beam melting [11]. As shown in Fig. 13.1, metallic AM processes for aerospace applications include direct metallic parts fabrication, rapid tooling, and metallic parts repair. Application examples include aero engine component manufacturing, functional graded materials, mold and die cores for casting, turbine blade repair, and so on. As for nonmetallic parts such as plastics, ceramics, sand, and composite materials, the typical available AM technologies are stereolithography [12], multijet modeling [13], fused deposition modeling (FDM) [14], freeze-form extrusion fabrication [15], and three-dimensional printing (3DP) [16]. The application areas of nonmetallic parts include rapid prototyping, fixtures, and interiors, among others.

13.2.2 Directed energy deposition in aerospace applications

DED processes [1] enable the creation of parts by melting material as it is being deposited. Although this basic approach can work for polymers, ceramics, and metal matrix composites, it is predominantly used for metal powders or wires. A wide range of metals and alloys, such as titanium, inconel, stainless steel, aluminum, and their alloys, is broadly applied in the aerospace industry and can be fabricated by DED processes. DED processes use a focused energy source (a laser beam, electron beam, or arc) to locally melt feedstock material (powder or wire) and build up three-dimensional (3D) components. Compared with PBF processes, multiple-axis deposition (such as additional rotary axis for substrate) and multiple material delivery (such as multipowder hoppers) can be used in DED processes. In addition, DED processes can also be easily integrated with conventional subtractive manufacturing for finishing machining. The multiaxis deposition capability of DED processes enable the fabrication of complex geometry parts without support structures, such as thin-walled structures, overhauling, and inner channel feature parts for aerospace components. DED processes can also produce functionally graded material (FGM) parts with multiple powder hoppers with different materials. Compared with the welding process, the low heat input along with the DED process's clamping flexibility can be adopted for repairing high-

value aerospace components such as turbine blades, blisks, and engine combustion chambers.

DMG Mori [17] developed the LASERTEC 65 3D hybrid manufacturing system (AM and subtractive manufacturing) using the LMD process. The hybrid manufacturing system has automated switching between laser deposition and milling with shuttle handling via the HSK interface. The large work area can support pieces with dimensions up to 500 mm in diameter and 350 mm high, a maximum weight of 600 kg, and a layer thickness varying from 0.1 to 5 mm. It is 10 times faster than the current powder bed process, and machining can be completed without a process chamber (works with most materials). Fig. 13.2 shows an example of a turbine housing made from stainless steel using the hybrid manufacturing process. The dimensions of the turbine housing are 180 × 150 mm, and build-up time is 230 min for deposition and 76 min for milling. This hybrid manufacturing process produces quality finished parts by combining the precise accuracy of CNC machining and the freeform fabrication capability of the AM process.

TWI [18] adopted a five-axis LMD process for overhanging geometries without support mechanisms. A helicopter engine combustion chamber, which is a thin-walled structure, was successfully built using this process (as shown in Fig. 13.3), with an accuracy of 0.8 ± 0.9 mm. Mechanical testing showed that wall density was more than 99.5% throughout the whole part. A total of 700 g of powder were fused in the part and 1.2 kg passed through nozzle, which means there was about 70% powder efficiency and the deposition rate was around 0.9 kg/h. The buy-to-fly ratio was obviously less compared with subtractive machining. This combustion chamber was 300 mm in diameter and 90 mm high, with a build time reduced from months to 7.5 h.

Optomec [19] developed a five-axis hybrid manufacturing system using the LENS process. The LENS 850-R system has a large work envelope (900 × 1500 × 900 mm) to build or repair large-volume components such as blisks, impellers, and shafts. The deposition rates are up to 0.5 kg/h for standard steels, titanium, and nickel alloys.

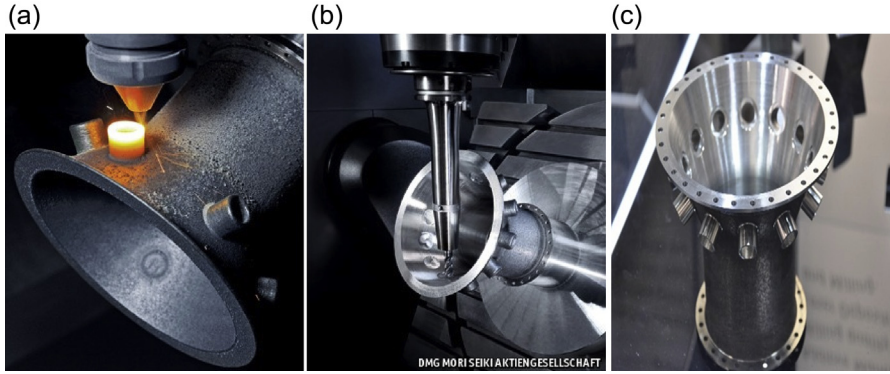

Figure 13.2 Turbine housing fabricated by the LASERTEC 65 3D System using (a) multiaxis deposition and (b) multiaxis machining. (c) Finished part.
Courtesy DMG Mori and Siemens.

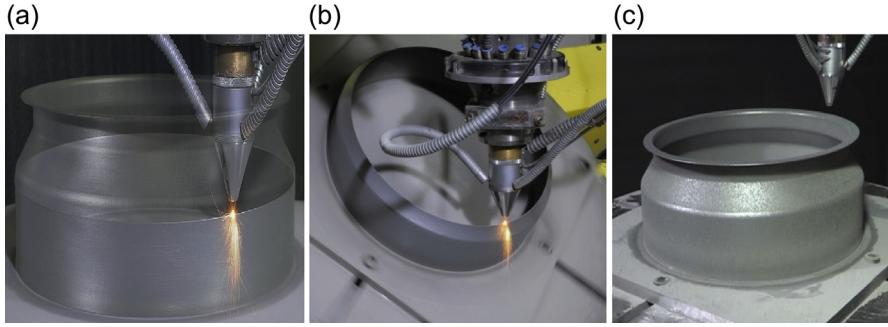

Figure 13.3 IN718 helicopter engine combustion chamber fabricated by a five-axis LMD process: (a) deposition showing the 2.5-dimensional tool path; (b) multiaxis deposition; and (c) the finished part.
Courtesy TWI.

Graded materials can be deposited by multiple powder feeders (two feeders hold up to 14 kg of powder each in the LENS 850-R system). As shown in Fig. 13.4, a one-sixth-scale mixing nozzle for a gas turbine exhaust was fabricated for Bell Helicopter using the LENS process.

In addition to commercial applications in the aerospace industry, there are also examples from academia. Liou et al. [20] developed a hybrid process combining multi-axis laser deposition and CNC machining. The hybrid process provides greater build capabilities in accuracy and surface quality for freeform fabrication, which was successfully applied to build and repair functional metallic parts. Xue and Islam [21], from the Integrated Manufacturing Technologies Institute of the National Research Council in Canada adopted the LMD process to directly fabricate metallic components.

Figure 13.4 Exhaust duct fabricated using the laser engineering net-shape process.
Courtesy Optomec.

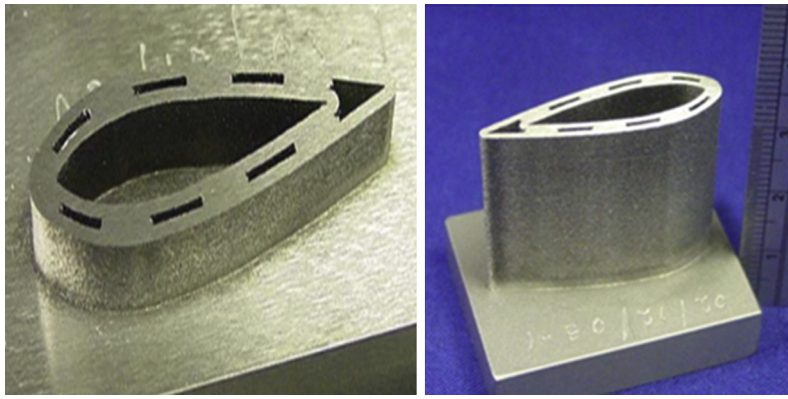

Figure 13.5 Ti-6Al-4V airfoils with embedded cooling channels built using the laser metal deposition process.
Courtesy Integrated Manufacturing Technologies Institute of the National Research Council, Canada.

Materials including nickel-based IN-625 and IN-738 superalloys, titanium-based Ti-6Al-4V alloy, cobalt-based Stellite 6 alloy, and iron-based CPM-9V tool steel were investigated. Mechanical property testing showed that the LMD-processed materials are comparable to, and sometimes better than, conventionally cast and wrought materials. As Fig. 13.5 shows, the LMD process has been used successfully to build net-shape Ti-6Al-4V airfoils with embedded cooling channels, which accurately represent the geometric features described in the computer-assisted design (CAD) model.

13.2.3 Powder bed fusion in aerospace applications

Different from the DED process, PBF-based AM processes spread a powder layer onto a substrate plate and selectively melt the powder with a focused energy source (a laser beam or electron beam) to build 3D parts. A wide range of materials—typically stainless and tool steels, titanium and its alloys, nickel-based alloys, and some aluminum alloys—are available for aerospace applications using PBF-based AM processes. A key advantage of the PBF process is that it can serve as an in-process support structure for overhangs and undercuts, and therefore complex shapes with a high geometric accuracy (±0.05 mm) can be manufactured; this separates this AM technology from the DED process [22]. It provides a great capability for optimizing the topology of component design and functional integration for aerospace applications. Available commercial systems include LaserCUSING from Concept Laser, 3DP from ExOne, direct metal laser sintering from EOS, SLM from Renishaw and SLM Solutions, and electron beam melting from Arcam.

GE Aviation [23] uses EOS's metal PBF machine to produce their next-generation jet engine components using the direct metal laser sintering process. The AM-fabricated part that gets the most attention is the new fuel nozzle shown in Fig. 13.6. Each LEAP engine has inside it 19 fuel nozzles created via 3DP. The new design features

Figure 13.6 GE Leap Engine fuel nozzle created using direct metal laser melting via the EOS metal powder bed fusion machine.
Courtesy GE Aviation and EOS.

have more intricate cooling pathways and support ligaments, which result in five times the service life compared with the predecessor part made by conventional manufacturing. The AM process allows engineers to use a simpler design that reduces the number of brazes and welds from 25 to only 5; the number of parts used to make the nozzle was reduced from 18 to 1. In addition, the weight of these nozzles is 25% lighter than that of the predecessor part.

Concept Laser [24] adopted the SLM process to fabricate aircraft components with a "bionic" design using their LaserCUSING system. An example of the bracket connector used in the Airbus A350 XWB is shown in Fig. 13.7. The bone-like porous structure significantly reduces the weight. The component was previously a milled part made of aluminum. Now it is made of titanium using AM and is significantly lighter. The new structure design is more than 30% lighter than conventional designs realized using casting or milling processes. The considerable weight reduction results in lower fuel consumption and the potential to increase the load capacity of the aircraft. On the other hand, toolless fabrication with the Concept Laser SLM process saves money and shortens the development time by up to 75%: Component development time was previously 6 months but is now down to 1 month.

ExOne [25] developed another powder bed−based AM process called "digital part materialization," otherwise known as 3DP. Since the process uses a selective-spraying liquid binder to solidify a layer, the material could be sand, metal, or glass. For the aerospace industry, 3DP in sand offers the largest build size available, capably of printing parts as large as 1800 × 1000 × 700 mm (70 × 39 × 27 in.). Standard foundry

Figure 13.7 The first titanium bracket connector produced using additive manufacturing on board the Airbus A350 XWB.
Reproduced from Airbus. Cabin bracket produced on Concept Laser's LaserCUSING machine.

industry materials are used, enabling the process to be easily integrated into existing manufacturing and foundry procedures. The large build volume and high build rate combine to make patternless production a reality for metal-based prototype castings and low-volume production using aluminum and copper alloys, gray and ductile iron, and magnesium. Applications include complex gear cases and covers, fuel tanks, transmission housings, and components requiring draft-free walls, lightweight engine parts, and structural hinges. The Airbus A320 door hinge cores and casting are large-component casting examples fabricated by 3DP [26].

13.2.4 Nonmetallic parts fabricated with additive manufacturing in aerospace applications

In addition to the fabrication of direct metallic components by AM processes for use in aerospace applications, the aerospace industry also has a great demand for the AM of non-metallic materials such as plastics, wax, sand, ceramics, and composites. The application areas cover rapid prototyping, tooling, and molding and direct part manufacturing. Available commercial systems for fabricating non-metallic parts include stereolithography, multijet printing from 3D Systems, FDM from Stratasys, and 3DP from ExOne, among others.

Stratasys [27] used its FDM system to discover a wide range of applications covering rapid prototyping, manufacturing tooling, and parts production with aerospace companies such as Piper Aricraft, Bell Helicopter, Aerialtronics, and NASA. The free-form fabrication capability provided by AM makes prototyping much easier, shortens the product development cycle, and reduces costs. For example, the Gas Turbine Research Establishment [28] used the FDM machine from Stratasys to prototype a jet engine. There are about 2500 engine components included in the assembly. In the past, the Gas Turbine Research Establishment would have taken a minimum of 1 year and paid an estimated $60,000 to build the physical prototype assembly

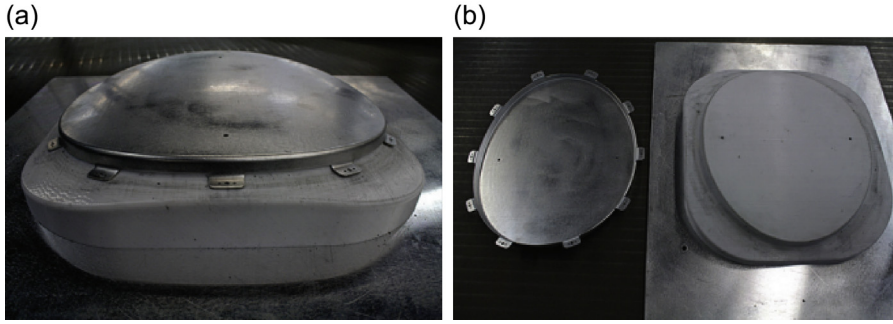

Figure 13.8 Piper Aircraft used fused deposition modeling (FDM) to make tools for hydroforming aluminum structural components. (a) An aluminum window pan on top of the FDM tool. (b) An aluminum window pan (left) and the FDM tool.
Courtesy Stratasys and Piper Aircraft.

by CNC machining. However, the AM process for prototyping cuts that time from 1 year to 6 weeks and reduces the cost from $60,000 to $20,000. Fit-for-purpose manufacturing tools made by AM have improved quality and production efficiency. For example, Piper Aircraft [29] uses the FDM process to make tooling for hydroforming aluminum structural components. Fig. 13.8 shows an aluminum window pan built using the tool made by the FDM machine. Piper Aircraft uses hydroforming to produce hundreds of aluminum structural components of aircraft, such as the inner frame, gussets, brackets, and skins. In the past, tools were produced by CNC machining for use in hydroforming machines. The amount of time required for programming and machining time, the necessary skilled labor, and the considerable material waste involved in machining resulted in machining complex form tools being very expensive. By contrast, FDM tooling reduces machining time by about 68%: from 14 to 4.5 days. High-performance thermoplastic can be adopted for hydroforming applications. For instance, ULTEM 9085, a flame-retardant resin, can withstand pressures up to 10,000 psi and can be produced by Stratasys's Fortus machine.

The FDM process can also be used to directly manufacture aircraft parts. Bell Helicopter [30] builds tough polycarbonate wiring conduits for their heavy-lift "tilt-rotor" Osprey; these conduits are shown in Fig. 13.9. Technicians installed the branching conduits in six mating sections inside the Osprey's twin vertical stabilizers for on-the-ground testing of its wiring. After some minor variations, the team requested five more complete sets for a total of 42 conduit models. It took only 2.5 days to make them all. In the past it would have taken take 6 weeks if the prototypes were made of cast aluminum. NASA [31] also adopted Stratasys's 3D printer for the Mars rover; about 70 of the parts that make up the rover were built digitally, directly from computer designs, in a production-grade heated chamber.

Another interesting example is a fully nonmetallic gas turbine engine fabricated by AM. The program, entitled "A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing," was sponsored by the NASA Aeronautics Research Institute [32]. The objective of this program was to use lightweight, high-temperature-resistant

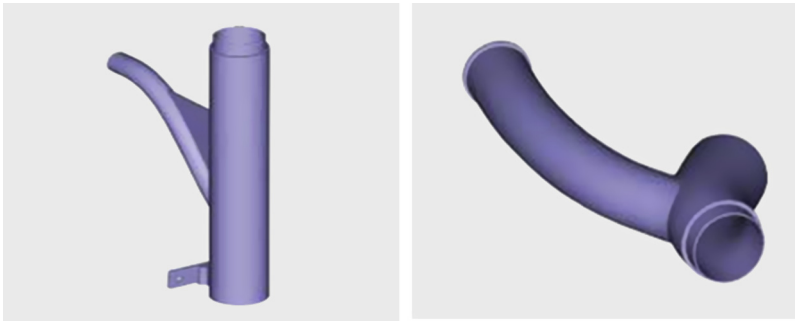

Figure 13.9 Polycarbonate wiring conduits made by fused deposition modeling. Courtesy Stratasys and Bell helicopter.

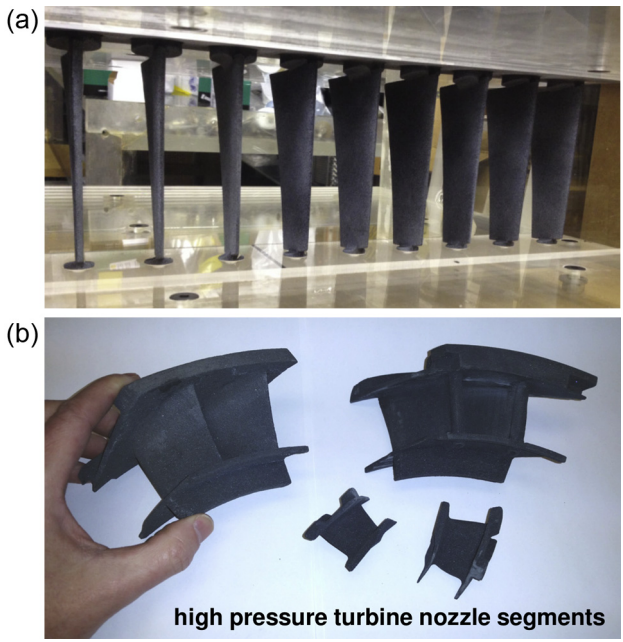

Figure 13.10 Nonmetallic gas turbine engine fabricated using additive manufacturing processes. (a) Compressor inlet guide vanes made from a polyetherimide composite using the fused deposition modeling process. (b) Turbine nozzle segments made from ceramic matrix composite using 3DP.
This excerpt is taken from 20150020812/GRC-E-DAA-TN25404, "A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing," and used with permission of NASA.

composite materials to improve engine efficiency. The first comprehensive evaluation of emerging materials and manufacturing technologies that enable fully nonmetallic gas turbine engines for reduced aircraft emissions, fuel burn, and noise was conducted. FDM was used to deposit polymer matrix composites, and the first polyetherimide composite was adopted to produce the compressor inlet guide vanes and acoustic liner (shown in Fig. 13.10(a)). The binder jet process was adapted for fabricating ceramic matrix composites (CMCs) using the M-Flex machine from ExOne. The first high-pressure CMC turbine nozzle segments were produced (Fig. 13.10(b)).

The aerospace industry also has a great demands on ceramic components, especially those made from ultra-high-temperature ceramics (UHTCs), such as ZrB_2, ZrC, TiC, and others, which have an excellent capability to withstand extreme high temperatures and tough chemical environments. Such parts can be applied in hypersonic flight systems and rocket propulsion systems. Since UHTC components are extremely brittle, it is difficult to fabricate them using a conventional subtractive manufacturing process. The AM process provides a great potential to make complex geometric UHTC components for the aerospace industry. Leu et al. [33] used ZrB_2 by selective laser sintering to fabricate a fuel injector strut with crossing channels inside that could potentially be used to provide resistance to extremely high temperatures in a hypersonic aircraft engine. Leu et al. also developed free-form extrusion fabrication for ceramic components.

13.3 Aerospace component repair with additive manufacturing

13.3.1 Background

13.3.1.1 Why repair aerospace components?

High-performance aerospace parts such as compressors, blisks, turbines, blades, and airfoils are expensive because they are typically made from high-value materials (ie, Ti-6Al-4V and Inconel 718) and involve complex processing during manufacturing [34]. Aerospace components may be subject to corrosion, impacts, variable thermal cycles and stresses, and other conditions that could cause defects or cracking during the service life. Fatigue and stress cracks are common initiators of failures that cause high-performance and high-value components to be scrapped. Defects such as milling ball indentation and cutter pull out may also occur during the manufacturing process. Because of the extreme cost of materials and labor for fabricating high-value components, it is necessary to repair those components instead of replacing them.

13.3.1.2 Why use additive manufacturing for repair?

Conventionally, the welding process has been used for repair. One of the first methods was tungsten inert gas welding [35]. This method is easy to perform, but it produces a lot of heat that can cause high residual stresses, resulting in distortion and heat-related effects in the base metal [36]. Plasma transferred arc welding [37] and electron beam

welding [38] are alternative processes that satisfy a lower heat input but need a more complex and expensive apparatus. The high-velocity oxyfuel thermal spraying technique [39] is used in many industries. There is less component distortion than with tungsten inert gas welding, and it has many advantages over plasma spraying, including deposition of a thicker and lower porosity coating. However, control of the depth and spread of the deposited material is not possible. In conclusion, conventional welding processes and thermal spraying techniques do not allow control of the deposit of exact materials with low input heat to melt and bond materials to the base metal.

AM technologies, through adding materials layer by layer to make parts, provide new opportunities to repair high-value metal components. The basic principle of the AM process used for repair is a laser beam that creates a metallurgical bond between the damaged surface area of a part, known as the substrate, and the added repair material, which is a metal powder [40]. For example, the LMD process could deposit local powder to the defect area according to the defect geometry. Compared with conventional repair techniques, the low input heat of AM leads to a small heat-affected zone in the surrounding substrate materials, causing minimal distortion, which allows AM to be used to create thin-walled structures such as wing spars or bulk heads for aircraft [41]. Distortion-sensitive components or components made by "nonweldable" materials that previously had to be scrapped because of the lack of a suitable repair technique can now be repaired with AM [7].

13.3.2 How does additive manufacturing work for repair?

13.3.2.1 Hybrid manufacturing process for repair

As illustrated in Fig. 13.11, a typical layout of the hybrid manufacturing process for component repair includes two major systems: an LMD system and a CNC milling machine system. The LMD process provides the ability to spread metal powder locally in the defect area. Combining AM and CNC results in a hybrid process that can provide greater build capability, better accuracy, and better surface finishing because the benefits of both processes are included [42,43]. In addition, the multiaxis CNC machine is able to do multiaxis deposition and machining for complex aerospace components such as blisks and turbine blades.

13.3.2.2 General repair process

In general there are three stages for the repair process: the repair preparation stage, the manufacturing stage, and the evaluation stage, as shown in Fig. 13.12. During the first stage, repair preparation, the worn component is evaluated in terms of whether it is cost-effective to repair it using the AM process, whether there was a collision with the deposition nozzle, whether the defect area needs machining, and whether the defect surface is accessible by the powder. After evaluation, the worn component is measured and compared with its nominal CAD model to extract the worn area. Common measurement methods, such as a touch trigger probe, charge-coupled device camera, and laser sensor,

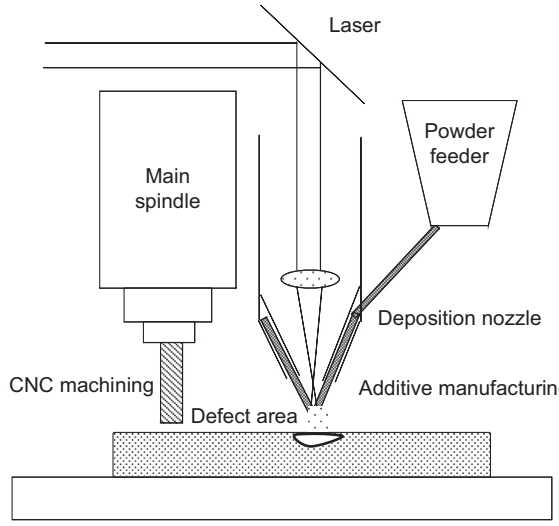

Figure 13.11 Hybrid manufacturing process for component repair.

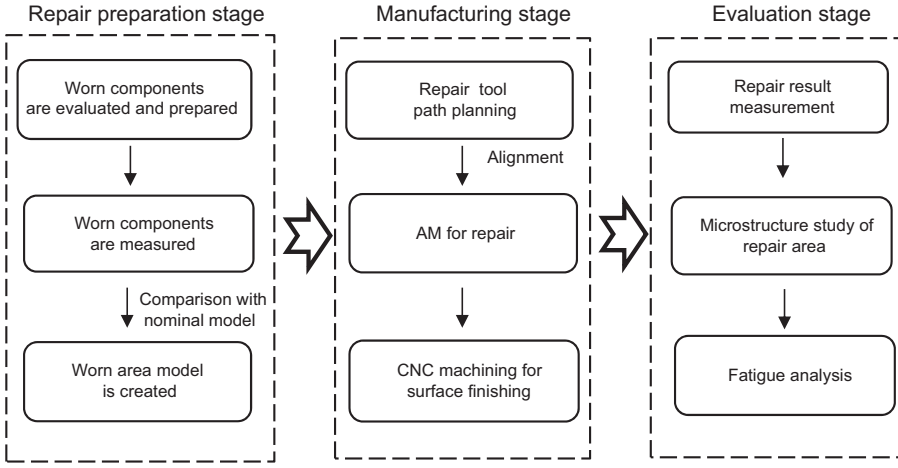

Figure 13.12 Overview of the general repair process. *AM*, additive manufacturing; *CNC*, computer numerical control.

can be divided into two categories: contact and noncontact [44]. The second stage of repair is the manufacturing process, during which the deposition tool path is generated according to the model of the worn area, and the hybrid process is adopted to repair the worn area and surface finishing. The final stage is evaluation of repair, when the resulting repair is measured and evaluated in terms of component tolerance. Mechanical properties such as ultimate tensile strength, yield strength, and hardness can be tested and microstructures can be studied. Fatigue analysis is also necessary to represent the repair

quality. Because components have different working environments and fatigue types, fatigue analysis should correspond to the practical situation.

13.3.3 Repair examples for aerospace applications

Optomec [45] enables aircraft engine components to be repaired using the LENS process. LENS-based repair solutions can precisely add material to worn components to restore their geometry. Integrally bladed rotors, also known as blisks, are high-value components that may cost tens or hundreds of thousands of dollars to fabricate. Without repair, any single airfoil that is worn out causes entire blisks to be scrapped. For example, a T700 blisk that was made from AM355 steel and suffered from erosion on the airfoil's leading edges during service was repaired with the LENS process. Fig. 13.13 illustrates the repair of the leading edge of a Ti64 airfoil, the blisk after deposition, and the blisk after finishing. Optomec used a cobalt-based wear-resistant material to repair the leading edge. The unique capabilities of the LENS repair system include [45]:

- *Low heat input*: The airfoil does not distort beyond dimensional limits.
- *Small heat-affected zone*: This minimizes degradation of the mechanical properties of the airfoil.
- *Superior mechanical properties*: LENS Ti-6Al-4V fatigue properties are equivalent to those of the wrought material.
- *Excellent quality*: Full environmental control ensures extremely low microporosity levels.
- *Complex shapes*: Virtually any cutout can be filled.
- *Greater repair access*: Even areas not in the line of sight can be repaired.
- *Near net shape*: The shape minimizes finishing time.

RPM Innovations [41,46] demonstrated a low-wattage (<500 W) repair using the LENS process. A Ti-6Al-4V bearing housing from a gas turbine engine was repaired to demonstrate the repair process. The bearing seating area was worn to an out-of-tolerance condition, and the housing was considered scrap. The process was used to build up the worn area, which was followed by final machining to print tolerances.

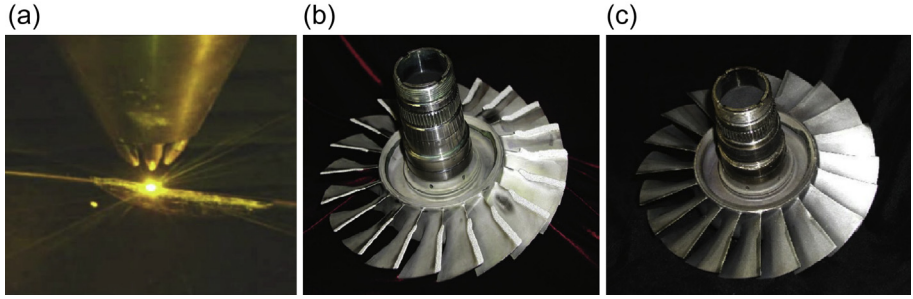

Figure 13.13 T700 blisk repair using the laser engineering net-shape process: (a) in-process repair of the leading edge of a Ti64 airfoil, (b) the blisk after deposition, and (c) the blisk after finishing.
Courtesy Optomec.

This housing was successfully repaired with no measurable distortion, and it completed an evaluation run in a test engine. The repair costs were about 50% of new pricing, plus it saved all of the materials that would be required to manufacture a new housing. Delivery for the repaired housing was a few days compared to several weeks for a new housing.

The European Commission [7] launched project FANTASIA (flexible and near-net-shape generative manufacturing chains and repair techniques for complex-shaped aero engine parts) in June 2006. The Fraunhofer Institute for Laser Technology (ILT) (Germany) joined the project with three major aero engine and component manufacturers, three repair excellence centers as end users, and five industrial partners. The objective was to reduce repair costs by at least 40% and reduce part repair turn-around time by 40% using AM. Some components that previously had to be discarded because of a lack of a suitable repair technique can now be repaired with the help of LMD. Fraunhofer ILT has been successfully certified by Rolls-Royce Deutschland for 15 different repair applications, two of which are for the repair of BR715 high-pressure turbine and BR715 high-pressure compressor front drum [7,47]. Geometric features on the surface of a BR715 high-pressure turbine case, such as bosses, brackets, and flanges, are repaired locally with just one layer deposited. Because of the minimized heat input of the LMD process, distortion of the component can be avoided almost completely. The contamination (oxidation)—free LMD result is guaranteed by a proper local gas shielding using a newly developed powder nozzle.

In addition to examples from commercial systems, universities and research institutes have also investigated using AM for repair applications in the aerospace industry. Gao et al. [48,49] proposed and developed an integrated repair solution adapted to worn component geometry for aerospace industries. Based on the scanned repair model with different defects, a reverse engineering—based geometry reconstruction method was developed to create a normal model of a worn component. Xue and Islam [21] demonstrated repair of the tips and seal of a damaged IN738 blade using the LMD process, as shown in Fig. 13.14. Richter et al. [50] applied LMD to repair a Ti6242

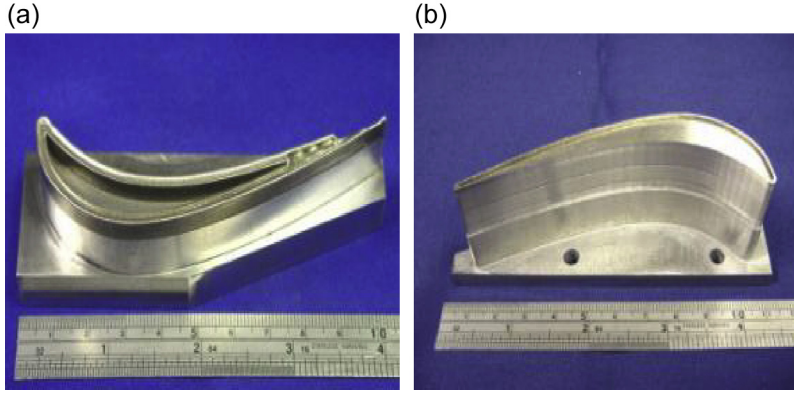

Figure 13.14 Repair to the tip of a cast IN738 blade (a) and the rebuild of the damaged seal (b). Courtesy Integrated Manufacturing Technologies Institute of the National Research Council, Canada.

blade and studied the microstructure, hardness, residual stress, mechanical properties, and fatigue of the repaired parts. Jones [51] combined laser cladding, machining, and in-process scanning in a single machine to realize automated component alignment, defect characterization, defect removal, and defect repair.

13.4 Challenges and potential future applications

13.4.1 Challenges of additive manufacturing for aerospace applications

AM technologies have been merged and developed for more than 25 years, transforming significantly from rapid prototyping to rapid tooling, direct part manufacturing, and repair. AM technologies have revealed great capabilities and the potential to reduce component weight, improve fuel efficiency, and reduce cost and turnaround time for aerospace applications. However, technical challenges of AM remain for aerospace applications, related to design, material characteristics, process control, process understanding, and modeling. The following summarizes the main challenges from publications and workshops [52].

- *Aerospace component design based on AM*: New designs based on the AM process, such as the new GE Aviation LEAP engine fuel nozzle and the "bionic" design of the bracket connector used in the Airbus A350 XWB, appeared in the aerospace industry and demonstrated the unique capabilities of AM processes, including their ability to fabricate complex geometry, handle functional complexities, and greatly enhance the freedom of designers. Progress is still required for conceptual design methods to aid designers in defining and exploring design spaces enabled by AM, methods for simultaneous product-process design and multifunctional design, and methods by which to assess lifecycle costs and the effects of parts and products fabricated by AM. A new foundation for CAD systems that overcome the limitations of parametric, boundary representation solid modeling in representing very complex geometries and multiple materials is needed [53].
- *Material characteristics for aerospace components fabricated by AM processes*: AM processes offer the unique advantage of fabricating difficult-to-machine materials, such as titanium alloys, nickel alloys, special steels, and ceramics, for the aerospace industry. However, there is no standard material characteristics database within the AM industry to provide mechanical properties fabricated by different AM processes, such as specifications of the mechanical properties of available materials and more detail on how parts made from these materials perform [54]. Engineers and designers cannot design without fully understanding the properties of the materials used to manufacture the parts being designed. If the properties for AM materials are not available, designers will not consider AM as a manufacturing method [52].
- *Process control*: For the AM process to be widely accepted by the industry, the ability for predictable, repeatable, consistent, and uniform fabrication is critical. In-process monitoring, closed-loop feedback, and building process-structure-property relationships modeled and integrated with CAD/E/M tools for each material and process are needed [55]. In situ sensors are an area that should be examined to provide nondestructive evaluation and enable early defect detection, particularly relating to thermal control. Better process controls could also lead to decreased downtime, which is currently a major issue for many machines and processes [55].

- *Process understanding and modeling*: New physics-based models of AM processes are needed to understand and predict material properties such as surface roughness and fatigue [56], especially for aerospace components working in extreme environments. A better understanding of the basic physics could then potentially lead to predictive modeling, allowing designers, engineers, scientists, and users to estimate the functional properties of the part during design and tweak the design to achieve the desired outcomes [52].

13.4.2 Potential future applications

In the past, the aerospace industry demonstrated many application areas and examples of topological optimization, functional integration, and direct fabrication for parts with complex geometry and new materials. AM applications in the aerospace industry especially focus on the design, fabrication, and repair of aero engine components. The following potential applications of AM are expected in the aerospace industry in the near future:

- *AM for the design of aircraft components*: AM provides a promising opportunity to design multifunctional or integral aircraft components that could reduce assembly or connection, simplify the design and manufacturing process, eliminate fixture and tools, and save materials and fuel costs. As a structure component with an internal channel, similar to airfoils, upgraded functional components could be realized by integrating acoustic and thermal insulation into aircraft parts or by embedding entire sensor/actuator systems, including electronic wiring and connectors. This can contribute to the realization of self-optimizing parts [57]. Integral aircraft components without joints enhance the design of parts for improved connectivity. The main purpose is to replace connectors, such as bolts and screws, which weaken the structural integrity and also represent a considerable cost factor [58].
- *Fabrication of large-scale aerospace components using AM*: While smaller aircraft parts are already being developed using AM techniques, the aerospace industry also envisions printing large-scale components, such as an entire airplane wing, in the future. The current AM techniques have limitations for fabricating large-scale objects because with the increase in dimensions, the internal stresses cause distortion. A recent technique developed by BAE Systems allows the new possibility to relieve stress by using an ultrasonic tool to strike metal parts repeatedly as each layer is built [59].
- *Manufacturing on demand*: Manufacturing on demand refers to the flexibility of AM technologies to produce parts "just in time". Storage costs can be reduced significantly. Furthermore, on-demand production fosters the intactness of parts because no damage can occur during storage [55]. In addition, printing parts on demand directly in space would significantly reduce the cost and planning cycles required to send a rocket into space with the necessary replacement and repair tools. On-demand 3DP of parts in space is currently being investigated by groups like Made in Space and Lunar Buildings. In collaboration with NASA, Made in Space is conducting zero gravity tests to experiment with 3DP on the International Space Station, which would allow astronauts to print tools and parts when required [56].
- *FGMs in aerospace*: FGMs can provide designers with a tailored material response and exceptional performance to thermal environments or mechanical loading. In the AM process, for instance, LMD can deliver different materials (usually through multiple feeding systems) to build tailored materials and properties for components with FGM. The potential FGM components could be used in severe thermal environments, such as aerospace and space vehicles. For example, space vehicles use ceramic tiles as thermal protection

from the heat generated during reentry into the Earth's atmosphere. However, these tiles are laminated to the vehicle's superstructure and are prone to cracking and debonding at the superstructure−tile interface as a result of the abrupt transition between thermal expansion coefficients. An FGM comprising ceramic on the outside surface and metal on the inside surface can eliminate the abrupt transition between coefficients of thermal expansion [60].

- *Automated repair process for aerospace components*: The aerospace industry and academia both have some cases for adopting the AM process to repair high-value components such as turbine blades, blisks, and bearing housings. This is cost-effective and reduces turnaround time for fabricating and replacing a new component. Currently, most of the time and cost are spent at the repair preparation stage. Future automated repair processes based on AM are expected to repair components effectively.

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